Operational Effects of the Longer and Wider Combination Vehicles on the Geometry of Diamond Interchanges

BALA M. RAJAPPAN AND C. MICHAEL WALTON

The Surface Transportation Assistance Act (STAA) of 1982 provided for more uniformity in size and weight regulation on federal aid highways, particularly for tractor-trailer combinations. Section 138/415 of that act also called for a feasibility study of a national intercity truck route network for commercial vehicles up to 118 ft long and 8.5 ft wide. The extra allowed length and width contributed significantly to the offtracking characteristics of these long combination vehicles (LCVs). The objective of the research described in this paper was to assess the operational impact of the LCVs on the geometry of diamond interchanges located along Interstate highways in Texas. The assessment was done by randomly sampling diamond interchanges and simulating all possible turn measurements of LCVs at their terminals. The movements were simulated with the computerized truck offtracking model (TOM). Results included the data collected on all interchanges located along Interstate highways in Texas and interval estimates of the proportion of diamonds with inadequate geometry, that is, pavement widths at ramp terminals inadequate to accommodate the LCVs. Ninety-nine percent confidence intervals were also estimated for the extra pavement widths required to prevent the LCVs from damaging pavement edges and other roadside appurtenances at the ramp terminals.

In past research studies, it was concluded that increasing need and demand for goods transported over highways may require a substantial increase in the number of commercial trucks within the next few years unless more goods are carried per power unit. Fuel shortages and environmental factors may become more critical, requiring almost all transportation modes, including highways, to use more efficient and productive equipment and operational procedures.

More than 30 years of operation and development has produced highway truck combinations that can haul more goods while conserving fuel and reducing the effects on highway pavement and bridges. These more productive combinations, represented by adding another trailer to present-day conventional truck combinations, are referred to as "long combination vehicles" (LCVs). Due to interest in LCVs, federal legislation through the 1982 Surface Transportation Assistance Act (STAA) and actions taken in some states have called for the elimination or reduction of truck size restrictions. The LCVs have lengths up to 118 ft and widths up to 8.5 ft. LCV truck combinations include turnpike doubles, Rocky Mountain doubles, and triples.

The extra length and width of the LCVs contribute significantly to their increased offtracking characteristics that could cause severe damage to the pavement edges and other roadside appurtenances at the existing interchanges, especially the diamond interchange ramp terminals. Offtracking is a condition in which the rear wheels of a vehicle negotiating a turn trace a track within the track traced by its front wheels. Another term that is used as frequently as offtracking is the "swept path," which can be defined as the radial distance between the turning paths of the outer front wheel and the outside of the rear wheel nearest to the center of the turn. Figure 1 shows the definitions of offtracking and swept path. Actual over-the-road operations tests conducted in the past have shown that the LCVs encounter critical problems while traversing highways and interchanges of the latest design *(1, 2)*.

The objective of this paper is to provide an overview of research conducted to assess the adequacy of the geometry of existing diamond interchanges in accommodating the offtracking characteristics of LCVs. The results of the assessment and conclusions are based on randomly sampled diamonds located along Interstate highways in Texas. The assessment comprises three major objectives. First, to identify the factors that influence the amount of pavement area available for turning maneuvers by the LCVs at the diamond interchange ramp terminals. In order to achieve this objective, the analysis of variance (ANOVA) procedure was used to screen the data collected from the geometry of diamond interchanges sampled and to determine the independent factors involved in describing the dependent variable. The dependent variable is the amount of pavement area available. The second objective was to determine the proportion of diamonds in Texas that could not adequately accommodate the LCVs. The third objective was to determine the extra pavement width required at these ramp terminals to adequately accommodate the LCVs without damage to pavement edges and roadside appurtenances.

DATA COLLECTED ON DIAMOND INTERCHANGES

In achieving the objectives, an inexpensive and expedient technique, the computerized truck offtracking model (TOM), was used to simulate LCV turning movements on existing interchanges. The availability of plan drawings with configurations and dimensions of existing interchanges from the Texas State Department of Highways and Public Transportation (SDHPT) made possible the sampling of many diamond interchanges. Before sampling, however, all the diamond interchanges lo-

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Center for Transportation Research, Bureau of Engineering Research, The University of Texas at Austin, Austin, Tex. 78712.

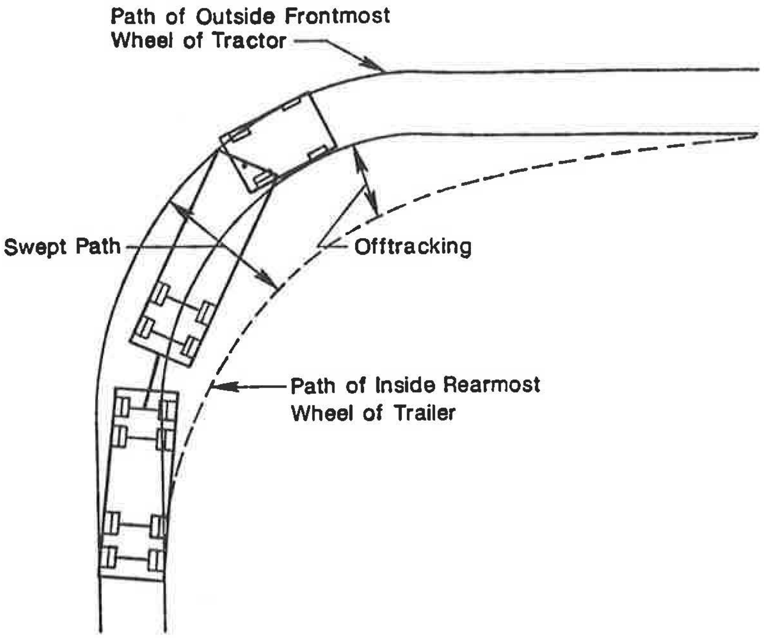


FIGURE 1 Offtracking and swept path of a combination vehicle.

cated along the Interstate highways in Texas, the types of crossroads, and their control and section numbers were inventoried *(3)*.

The diamond interchange is the simplest and also the most common type of interchange in Texas. A full diamond interchange is formed when a one-way diagonal-type ramp is provided in each quadrant. The ramps are aligned with free-flow terminals on the major highway, and the left turns at grade are configured to the crossroad. The diamonds are further classified into conventional diamonds, conventional split diamonds, split diamonds with jug handle ramps, diamonds with turnarounds, and X-diamonds. A conventional diamond is the full diamond, which is the most common. A conventional split diamond is the conventional diamond with each pair of ramps connected to separate crossroads about a block apart. An X-diamond is a diamond with exit and entrance ramps provided before and after the crossroad, respectively, forming an X pattern. Diamonds of this design are common in some urban areas in Texas, such as Houston. A diamond with a turnaround is the conventional or split diamond provided with turnaround facility. A split diamond with jug handle ramps is the unique type of diamond commonly found in the rural areas of Texas, for which almost all the crossroads are low-design types.

Diamond Interchange Population

A total of 1,337 diamond interchanges were identified along the Interstate highways in Texas. Of these, 35 percent were located in urban areas and the remaining 65 percent in rural areas (Figure 2). Approximately 86 percent of the diamonds were conventional diamonds; the split diamonds, split diamonds with jug handle ramps, diamonds with turnarounds, and X-diamonds accounted for 2.1, 4.7, 5.9, and 1.3 percent, respectively, of the total population of diamonds.

Data Collected on the Geometry of Diamond Interchanges

The identification of all diamond interchanges facilitated random sampling for a statistical analysis of their geometry. The availability of the TOM and the plan drawings of interchanges made possible the selection of a large enough sample size of diamonds. In order to examine the interchange geometry and its compatibility with LCVs, all possible turning movements at the ramp terminals were analyzed. The three most common cases of ramp terminals identified among the sampled diamond interchanges are as follows:

Case 1. Two-way crossroad, one lane each direction, one-way exit and entrance ramp with one lane each direction; eight turning movements possible.

Case 2. Two-way crossroad, two lanes each direction, one-way exit and entrance ramp with one lane each direction; eight turning movements possible.

Case 3. Two-way crossroad, two lanes each direction, two-way frontage road with one lane each direction; sixteen turning movements possible.

Figure 3 shows the configuration of a diamond interchange with all turning movements numbered for Case 1. The computer model used for the analysis requires an input path for each turning movement. For example, the input path for a right turn was the path the tractor's frontmost left wheel followed. For a left turn, the input path was the path taken by the frontmost right wheel. These input paths were drawn manually for each turning movement on each interchange sampled. The data collected for each turn were the distances between the input path and the pavement edge.

Four assumptions were made for the input paths. First, the drivers follow simple curve turns. Simple curve turns assumed

Types of Interchanges	Urban	Rural	Total	% of Total
Conventional Diamond (CDI)	354	792	1146	86
Split Diamond (SDI)	23	6	29	2
Split Diamond w/ Jug Handle Ramps (SDJ)	4	60	64	5
Diamond with Turnaround (DIT)	69	11	80	6
X - Diamond (XDI)	18	0	18	1
Total	468	869	1337	100

FIGURE 2 Summary of data collected on diamond interchanges.

in order to facilitate data collection were considered valid in describing the pavement area available at the ramp terminals. Second, the minimum radius of turns is 45 ft for the outermost front wheel. The 45-ft minimum turn radius was in accordance with the AASHTO recommendation *(4)*. The third assumption was that LCVs do not use the opposing traffic lanes during turn maneuvers. This assumption prevents the LCVs from impacting the opposing traffic flow and reduces the potential for accidents, implying that the LCVs operate under normal conditions. Because the data collected were representative of the available pavement area, the LCVs were further assumed to use illegal left and right turning movements if extra lanes were available in the direction of travel *(5)*.

Three measurements *DB*, *DM*, and *DE* were made at each turning movement. Figure 4 shows the locations of the measurements for a left-turn movement from an exit ramp into a crossroad with two lanes in each direction. *DB* and *DE* measure the perpendicular distances from the tangents at the beginning and end, respectively, of the simple curves to the pavement edges. *DM* measures the maximum perpendicular distance

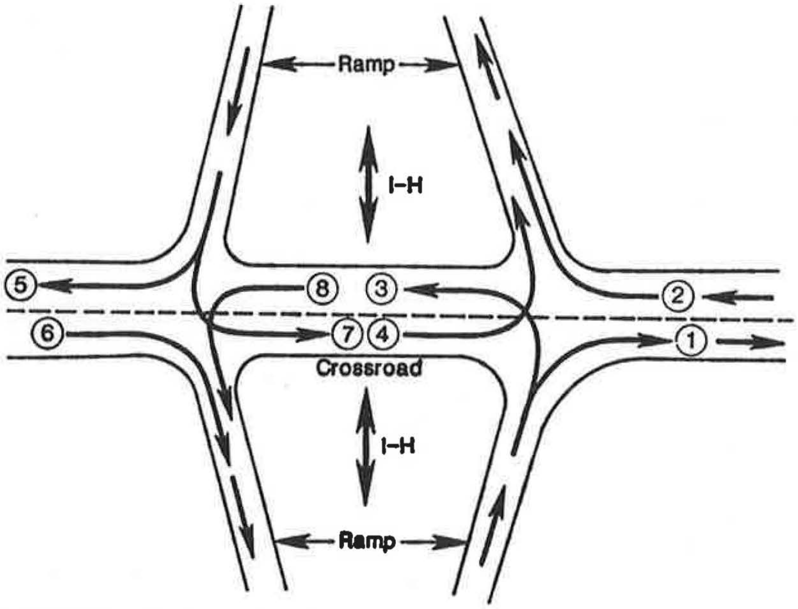


FIGURE 3 Configuration of a diamond interchange for Case 1.

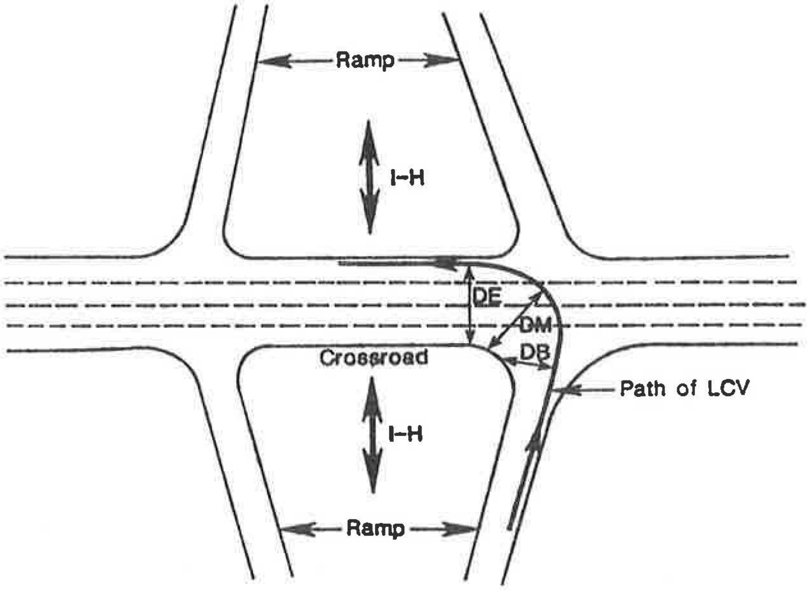


FIGURE 4 Locations of distances *DB, DM,* and *DE* for a left turn.

from the tangent to the pavement edge. The location of the tangent on the curve for maximum distance between the curve and the pavement edge occurs in most cases between the middle and end of the curve. These three measurements for each turning movement are the data for the analysis of variance (ANOVA) to determine the factors that significantly influence the pavement area available at the diamond interchange ramp terminals.

ANOVA

The ANOVA procedure was done using the Statistical Analysis System (SAS) computer program. In order to do this procedure, all factors and their levels needed to be clearly defined. These factors could either be fixed or random. Fixed factors were those with all levels of interest to this study included in the analysis. Random factors were those with fewer than the population levels of the factors included in the analysis and assumed to randomly represent the interchange population. The analysis included five fixed factors and one random factor. These factors described the inference space for the assessment. The fixed factors were the geographic location of an interchange, crossroad type, movement type, direction of travel, and the locations where measurements were made along the input path. Figure 5 shows the factors and their levels. The random factor was represented by the random occurrence of the interchanges sampled.

Because 65 percent of the total population of diamonds was located in rural areas, a location factor *L* was introduced with two levels: urban and rural. This factor could be tested for significance of the effect of the geographic location of a diamond on the pavement area available at its ramp terminal. The factor *T* allowed a test on the effect of types of crossroads on the available pavement area. The types of crossroads included U.S. highway, state highway, farm-to-market (FM) road, and arterials. All other types, such as paved and unpaved, were ignored because they represented low design types that could only be used by LCVs intermittently, if at all. Interstate highways were not included as a crossroad type because the intersection of two Interstate highways generally requires a higher level of interchange, such as a full directional or semidirectional.

The effects of left and right turns were tested for significance by using the next major factor, movement type *M*, with two levels. Factor *C* was introduced to test the effect of the various directions of movements. Four different levels described the different movements, on the right and left frontage roads, and from ramp to crossroad and vice versa. The right side of an interchange was defined as the west side of a north-south Interstate highway, and as the south side of an east-west Interstate highway. The final factor *D* had three levels *DB*, *DM*, and *DE*, as shown in Figure 4. It was tested for significance of the locations of measurements along the input path.

In the ANOVA, each interchange was treated as an experimental unit. A total of 16 interchanges were subsampled from the original sample of 85 diamonds. Factors *L, T, M, C,* and *D* were fixed factors and thus did not have any random variance component associated with them. However, an additional factor *O* was introduced that represented the random occurrence of interchanges nested within the crossroad type *T* and location *L*. Two interchanges were randomly subsampled for each combination of location *L* and crossroad type *T*. For example, two urban diamonds with U.S. highways as crossroads formed two experimental units shown as 1 and 2 of random factor *O* in Figure 5. Interchange types 15 and 16 represented two diamond interchanges with arterials as crossroads, located in rural areas. Therefore, factor *O* represented the random occurrence of the 16 diamond interchanges located along the Interstate highways. The two random occurrences of interchanges or experimental units nested within crossroad type *T* and location *L* provided the errors needed to test the significance of the factors involved. The 16 interchanges subsampled had the data needed to fill all the cells shown in Figure 6, thus allowing

FACTORS	LEVELS OF FACTORS
LOCATION, L	1 - Urban 2 - Rural
TYPE OF CROSSROAD, T	1 - U.S. Highway 2 - State Highway 3 - F.M. Road 4 - Arterial
MOVEMENT TYPE, M	1 - Right Turns 2 - Left Turns
DIRECTION, C	1 - Ramp to Crossroad on Right Frontage Road 2 - Crossroad to Ramp on Right Frontage Road 3 - Ramp to Crossroad on Left Frontage Road 4 - Crossroad to Ramp on Left Frontage Road
SPACE, D	1 - Distance Available (DB) at the Beginning of Turn 2 - Maximum Distance Available (DM) between the beginning and the end of turn 3 - Distance Available (DE) at the End of Turn

FIGURE 5 **Factors and levels of factors.**

complete factorial split-split-split plot analysis *(6, 7)*. The data displayed were tested to be homogeneous at the 5 percent significance level using Bartlett's test.

The dependent variable was the measurement of *DB, DM,* and *DE* for each turning movement at each interchange sampled. Because the ANOVA model is a complete factorial one, it includes all the two-factor, three-factor, four-factor, and five-factor interaction effects. The interactions with the *O* factor or random occurrence were assumed to be normally and independently distributed with zero mean and variance d_0^2. The remaining fixed-factor interaction effects could be tested using *F*-tests for significance. The *F*-tests were made with the null hypothesis of no factor or interaction effects. All tests were made for $\alpha = 0.05$, implying that the probability of rejecting the null hypothesis when it should be accepted was 5 percent.

The ANOVA Linear Model

The ANOVA linear model consists of the following equation:

$$\begin{aligned} Y_{ijklmn} = {} & m + L_i + T_j + LT_{ij} + O_{(ij)k} + d_{(ijk)} + M_l + LM_{il} \\ & + LTM_{ijl} + OM_{(ij)k} + C_m + LC_{im} + TC_{jm} + LTC_{ijm} \\ & + OC_{(ij)km} + MC_{lm} + LMC_{ilm} + TMC_{jlm} + LTMC_{ijlm} \\ & + OMC_{(ij)klm} + D_n + LD_{in} + TD_{jn} + LTD_{ijn} + OD_{(ij)kn} \\ & + MD_{ln} + LMD_{iln} + TMD_{jln} + LTMD_{ijln} \\ & + OMD_{(ij)kln} + CD_{mn} + LCD_{imn} + TCD_{jmn} \\ & + LTCD_{ijmn} + OCD_{(ij)kmn} + MCD_{lmn} \\ & + LMCD_{ilmn} + TMCD_{jlmn} + LTMCD_{ijlmn} \\ & + OMCD_{(ij)klmn} \end{aligned}$$

($i = 1, 2$; $j = 1, 2, 3, 4$; $k = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16$; $l = 1, 2$; $m = 1, 2, 3, 4$; $n = 1, 2, 3$).

where

Y_{ijklmn} = measured distance (ft);
m = overall mean;
L_i = effect of the *i*th location (fixed);
T_j = effect of the *j*th crossroad type (fixed);
$O_{(ij)k}$ = effect of the *k*th occurrence (random) of an interchange at the *i*th location and *j*th crossroad

Location, L			1								2							
Crossroad Type, T			1		2		3		4		1		2		3		4	
Interchange Occurrence, O			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Movement Type, M	Direction, C	Distance, D																
1	1	1	24	24	24	32	40	19	26	33	24	18	18	15	18	20	22	24
		2	31	20	22	16	40	17	42	20	32	21	20	18	24	25	26	25
		3	26	28	22	30	32	35	32	26	25	12	18	12	12	10	12	22
	2	1	26	28	22	39	32	35	32	26	24	12	18	12	12	10	12	25
		2	31	20	22	20	40	17	42	20	35	21	20	18	24	25	26	30
		3	24	24	22	32	30	24	26	32	24	18	18	15	18	20	22	25
	3	1	24	24	24	32	33	48	26	33	24	18	20	14	18	20	22	25
		2	31	20	22	18	39	45	43	20	32	21	20	14	24	25	26	30
		3	26	28	22	22	36	35	32	26	25	13	14	17	12	10	12	25
	4	1	26	28	22	42	36	35	32	26	24	13	16	12	12	10	12	22
		2	31	20	22	47	40	18	43	20	36	21	20	12	24	25	26	25
		3	24	24	22	32	36	24	26	33	24	18	16	18	18	20	22	24
2	1	1	24	24	26	32	36	51	48	33	32	18	28	15	18	20	30	25
		2	43	41	54	60	40	77	42	66	49	27	32	20	32	28	45	30
		3	30	37	22	24	32	40	32	30	28	25	28	30	12	20	20	21
	2	1	30	37	62	24	41	40	34	30	28	25	32	28	12	20	20	24
		2	43	45	66	60	47	77	44	65	49	27	38	28	32	28	44	25
		3	24	24	26	32	24	52	48	32	32	18	30	30	18	20	30	24
	3	1	30	24	28	32	44	52	48	33	32	18	16	20	18	20	30	50
		2	43	42	62	53	48	78	43	66	50	27	16	30	32	28	44	25
		3	30	38	62	24	40	40	32	30	28	25	20	28	12	20	20	24
	4	1	24	38	62	24	32	40	34	31	28	25	24	27	12	20	20	21
		2	43	45	40	60	49	78	45	66	50	27	33	30	32	28	45	30
		3	24	24	28	32	48	52	47	33	32	18	24	20	18	20	30	25

FIGURE 6 Input data for the ANOVA procedure.

type, assumed normally and independently distributed with mean 0 and variance d_0^2;

$d_{(ijk)}$ = restriction error due to the movement type, direction of travel, and distance measured being carried out on the *i, j, k* interchanges *(6)*;

M_l = effect of the *l*th movement type (fixed);

C_m = effect of the *m*th direction of travel (fixed);

D_n = effect of the *n*th distance measured (fixed); and

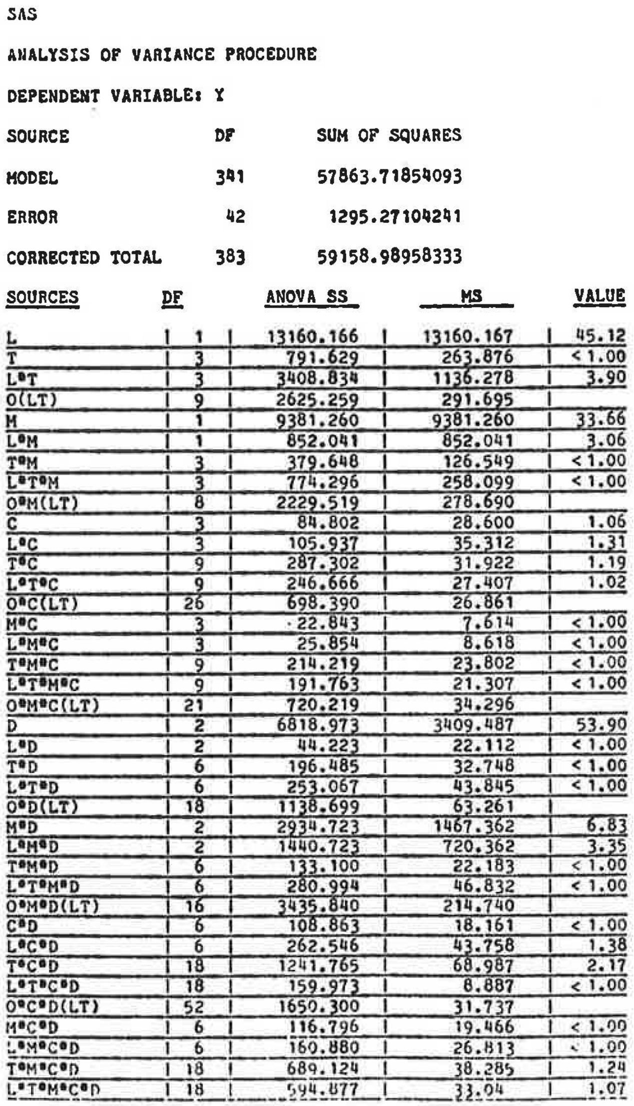
$OLTMCD_{(ij)klmn}$ = within error or the split-split-split plot error of the *n*th distance of the *m*th direction travel of the *l*th movement type in the *k*th occurrence of interchange at the *i*th location and the *j*th crossroad, assumed normally and independently distributed with mean 0 and variance d_0^2.

The remaining terms in the model are the interaction effects between the main effects L_i, T_j, C_m, D_n, and the random occurrence O_k.

Results of ANOVA

Figure 7 shows the results of the analysis of variance, which include sources of effects, corresponding degrees of freedom, ANOVA sum of squares, means squares (MS), and *F*-values. The effects were all tested with the corresponding error terms. For example, the main effects *L* and *T* and interaction effects *L*T* were tested with the whole-plot error, that is, with the MS of *O(LT)*, which is the SAS notation for $O_{(ij)k}$ in the ANOVA model. The effects of *M*, *L*M*, *T*M*, and *L*T*M* were tested with the split-plot error *O(LT)*M*, and so on.

Using the *F*-test, the main effects *L*, *M*, and *D* were found significant at $\alpha = 0.05$. Two two-factor interaction effects, *L*T* and *M*D*, and one three-factor effect, *T*C*D*, were also found significant at the same significance level. None of the four- or five-factor interaction effects were found significant. It was concluded that the location *L*, movement type *M*, and the three different locations along the input path *DB*, *DM*, and *DE* significantly affected the available pavement area at the ramp



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SAS

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: Y

SOURCE              DF       SUM OF SQUARES

MODEL              341       57863.71854093

ERROR               42        1295.27104241

CORRECTED TOTAL    383       59158.98958333

SOURCES        DF        ANOVA SS         MS          VALUE

L            |  1  |    13160.166  |  13160.167  |   45.12
T            |  3  |      791.629  |    263.876  |  < 1.00
L*T          |  3  |     3408.834  |   1136.278  |    3.90
O(LT)        |  9  |     2625.259  |    291.695  |
M            |  1  |     9381.260  |   9381.260  |   33.66
L*M          |  1  |      852.041  |    852.041  |    3.06
T*M          |  3  |      379.648  |    126.549  |  < 1.00
L*T*M        |  3  |      774.296  |    258.099  |  < 1.00
O*M(LT)      |  8  |     2229.519  |    278.690  |
C            |  3  |       84.802  |     28.600  |    1.06
L*C          |  3  |      105.937  |     35.312  |    1.31
T*C          |  9  |      287.302  |     31.922  |    1.19
L*T*C        |  9  |      246.666  |     27.407  |    1.02
O*C(LT)      | 26  |      698.390  |     26.861  |
M*C          |  3  |       22.843  |      7.614  |  < 1.00
L*M*C        |  3  |       25.854  |      8.618  |  < 1.00
T*M*C        |  9  |      214.219  |     23.802  |  < 1.00
L*T*M*C      |  9  |      191.763  |     21.307  |  < 1.00
O*M*C(LT)    | 21  |      720.219  |     34.296  |
D            |  2  |     6818.973  |   3409.487  |   53.90
L*D          |  2  |       44.223  |     22.112  |  < 1.00
T*D          |  6  |      196.485  |     32.748  |  < 1.00
L*T*D        |  6  |      253.067  |     43.845  |  < 1.00
O*D(LT)      | 18  |     1138.699  |     63.261  |
M*D          |  2  |     2934.723  |   1467.362  |    6.83
L*M*D        |  2  |     1440.723  |    720.362  |    3.35
T*M*D        |  6  |      133.100  |     22.183  |  < 1.00
L*T*M*D      |  6  |      280.994  |     46.832  |  < 1.00
O*M*D(LT)    | 16  |     3435.840  |    214.740  |
C*D          |  6  |      108.863  |     18.161  |  < 1.00
L*C*D        |  6  |      262.546  |     43.758  |    1.38
T*C*D        | 18  |     1241.765  |     68.987  |    2.17
L*T*C*D      | 18  |      159.973  |      8.887  |  < 1.00
O*C*D(LT)    | 52  |     1650.300  |     31.737  |
M*C*D        |  6  |      116.796  |     19.466  |  < 1.00
L*M*C*D      |  6  |      160.880  |     26.813  |  < 1.00
T*M*C*D      | 18  |      689.124  |     38.285  |    1.24
L*T*M*C*D    | 18  |      594.877  |     33.04   |    1.07
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FIGURE 7 Results of ANOVA.

terminals of diamond interchanges. Other main factors, such as the crossroad type *T* and the direction of travel *C* did not have significant effects on the available pavement area.

However, further analysis was done using the Bonferroni means comparison tests on the interaction effects that were found significant. These tests facilitated the investigation of which pairs of factors involved had means significantly different at the chosen level. Figure 8 shows the plots of the mean values of the dependent variable $\bar{Y}$ for every combination of geographic location *L* and crossroad type *T*. The tests revealed at a 95 percent confidence level that the difference between the pair of means at level 3 (FM crossroad) of the crossroad type *T* was significant. This significance meant that the compounded effect of the locations that were urban and rural and the crossroad type on the available pavement area at the diamond interchange ramp terminal was significant only for the FM crossroad.

Figure 9 shows the plot of the mean values of measurements $\bar{Y}$ versus the locations *D* of measurements on the input path for various levels of movement type *M*. The Bonferroni tests showed that the differences between values of $\bar{Y}$ for movement type *M* or left and right turns were significant only at the second level of factor *D*, which was the location along the input path where the maximum offtracking occurred. The difference between values of $\bar{Y}$ for the left and right turns at the beginning and at the end of input path curves was revealed to be insignificant at the 5 percent significance level. The tests also revealed that the differences between $\bar{Y}$ values for all combinations of the three-factor interaction *T*C*D* were insignificant at the 95 percent confidence level (5 percent significance level).

Interval Estimates for Proportion of Diamonds with Inadequate Geometry

The preliminary analysis determined that location and movement type directly affected the available pavement area at diamond interchange ramp terminals. It also revealed that the locations along the input path where the measurements were made also played a significant role in expressing the available pavement areas. Furthermore, the available pavement areas at diamond interchanges with FM crossroads and located in rural

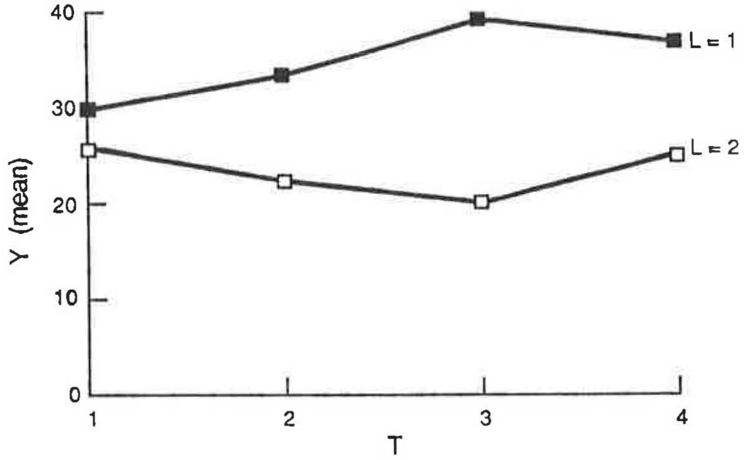

FIGURE 8 Plot of $\bar{Y}$ for two-way classification of L and T.

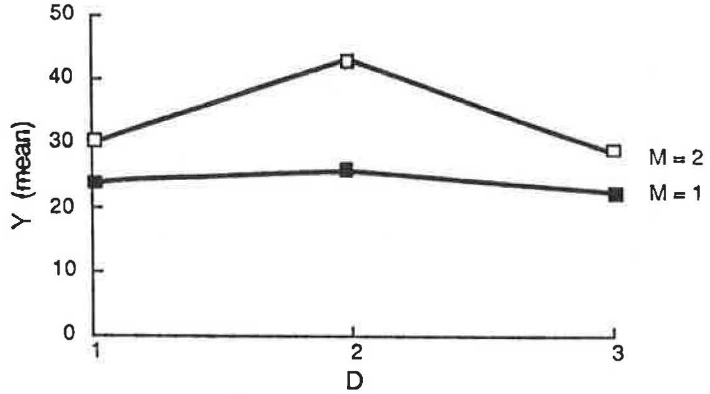

FIGURE 9 Plot of $\bar{Y}$ for two-way classification of M and D.

areas were significantly smaller than similar interchanges located in urban areas, and therefore were more critical. Other main factors such as the crossroad type, direction of travel, and other interaction effects were discarded as insignificant at the same confidence level.

The second objective of the research was to determine the proportion of diamonds with geometry inadequate to accommodate the turn maneuvers of the LCVs. A pilot sample of 16 diamonds revealed that 93.8 percent of all the diamonds had inadequate geometry. Because the ANOVA procedure determined that the geographic locations and movement types significantly affected the pavement areas, the proportions were estimated for both left and right turns at both urban and rural areas separately. The optimal sample size needed to determine the proportion at the 95 percent confidence level and standard error of 0.065 for rural diamonds was 53. The sample size for urban diamonds at a similar confidence level but with a standard error of 0.075 was 40. The final sample sizes of rural and urban diamonds actually used for analysis were 49 and 36, respectively. Table 1 presents the interval estimates for the proportion of diamonds with geometry inadequate to accommodate the turn maneuvers of the LCVs at the ramp terminals.

TABLE 1 INTERVAL ESTIMATES FOR PROPORTION OF DIAMONDS WITH INADEQUATE GEOMETRY

Diamond Interchanges	Interval Estimates	Confidence Level (%)
Urban right turns	$0.92 \le P \le 1.00$	95
Urban left turns	$0.84 \le P \le 0.99$	95
Rural right turns	$0.94 \le P \le 1.00$	95
Rural left turns	$0.83 \le P \le 0.97$	95

In this table, the percentage of urban diamonds with geometry inadequate for right turns ranged from 92 to 100 percent at the 95 percent confidence level. The percentage of similar diamonds with geometry inadequate for left turns ranged between 84 and 99 percent. The proportion of rural diamonds with geometry inadequate for right turn ranged from 94 to 100 percent at the 95 percent confidence level, and those with geometry inadequate for left turns ranged between 83 and 97 percent. The estimates also revealed that the proportion of diamonds incapable of accommodating the turn maneuvers by the LCVs was higher for the right turns than for the left turns.

Interval Estimates for Extra Pavement Width Required

The third objective was to estimate the extra pavement width required at the ramp terminals of diamond interchanges with inadequate geometry. The data collected on the sampled diamond interchanges included the values of the radii and degrees of turns for each movement analyzed. The radii of turns ranged from 45 to 450 ft, and the angles of turns were between 37 and 180 degrees.

In order to obtain the data for the estimates of extra pavement width required, the values of radii and angles of turns of every possible turning movement at the sampled interchanges were used. These values were input into the TOM with the dimensions of a chosen LCV type. The movements of the LCV were then simulated to obtain its swept path values. The simulations were repeated for every combination of radius and angle of turn collected to make comparisons between the actual pavement width available and the swept path values computed by TOM for the chosen LCV type. Actual measurements taken at existing sampled interchanges were *DB*, *DM*, and *DE*; equivalent TOM values were *BC*, *MOT*, and *FC*. Because the assessment was done for the worst case scenario, the LCV type used in the TOM was the 118-ft-long and 8.5-ft-wide turnpike double (consisting of two 48-ft trailers). The data for the estimates of extra pavement widths were the differences between the measured distances *DB*, *DM*, and *DE*, and the swept path values *BC*, *MOT*, and *EC*, respectively, computed by the computer model. The sample size for interval estimates for extra pavement width required was the total number of turning movements instead of interchanges. A total of eight cases were analyzed in accordance with the results of the analysis of variance. The cases are summarized by data presented in Table 2. The difference values at the beginning and at the end of input paths, that is, *BC–DB* and *EC–DE* were not analyzed as different cases for the rural diamonds because they were not significantly different from the urban diamonds as shown by the Bonferroni test previously.

TABLE 2 DESCRIPTION OF CASES THAT REQUIRE EXTRA PAVEMENT WIDTH

Case No.	Location *L*	Movement Type *M*	Extra Pavement Width Needed (ft)
1	Urban	Right	*BC – DB*
2	Urban	Right	*MOT – DM*
3	Urban	Right	*EC – DE*
4	Urban	Left	*BC – DB*
5	Urban	Left	*MOT – DM*
6	Urban	Left	*EC – DE*
7	Rural	Right	*MOT – DM*
8	Rural	Left	*MOT – DM*

Thirty-six urban diamonds and 49 rural diamonds produced approximately 680 turn movements that were divided between urban right, urban left, rural right, and rural left. The total number of observations available for each case ranged from 110 to 180. The dependent variable was the difference between the actual pavement width available at the ramp terminal of a diamond interchange and the swept path value produced by the TOM. Frequency distributions of the differences were plotted for each case (see Figure 10 for Case 1). Positive values indicated inadequate pavement width because the pavement widths measured were subtracted from the swept path values for the turnpike double LCV computed by the TOM. Negative values indicated surplus pavement widths.

The results of distributions for the eight cases are summarized in Table 3, which presents the mean, standard deviation, and *D* value for each case. The *D* value is a measure of maximum deviation used for the Kolmogorov-Smirnov test for normality.

Table 4 shows the 95 percent confidence intervals of the differences between the actual pavement widths available at existing diamond interchange ramp terminals and the swept paths of the turnpike double LCV as computed by the TOM for all the cases. The 95 percent confidence interval for extra

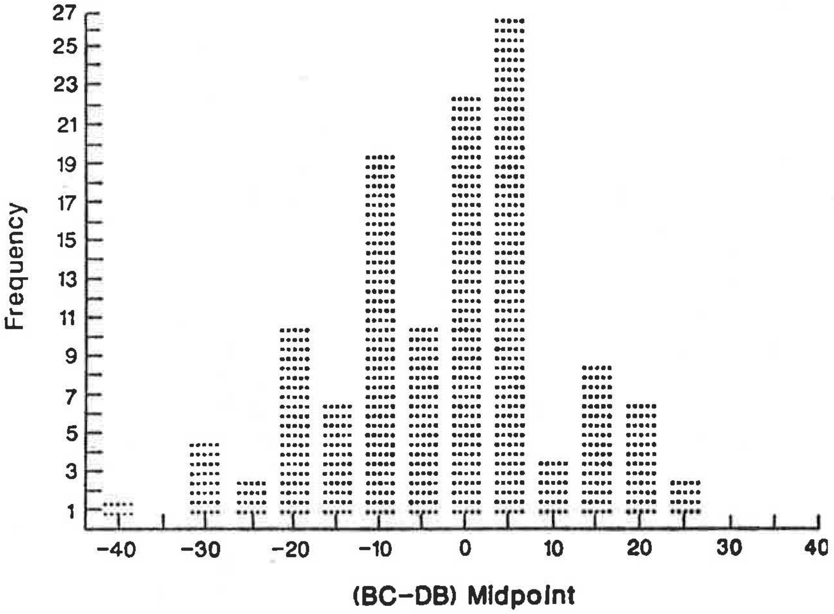

FIGURE 10 Distribution for Case 1.

TABLE 3 DISTRIBUTION STATISTICS FOR CASES THAT REQUIRE EXTRA PAVEMENT WIDTH

Case No.	Sample Size N	Mean	Standard Deviation	D-Value
1	119	–2.2	12.9	0.083
2	119	2.5	9.2	0.085
3	119	2.9	11.5	0.072
4	120	–3.5	10.8	0.092
5	120	–13.7	12.1	0.076
6	120	1.3	9.5	0.126
7	108	13.5	8.3	0.082
8	177	0.6	11.7	0.088

TABLE 4 INTERVAL ESTIMATES FOR CASES THAT REQUIRE EXTRA PAVEMENT WIDTH

	95 Percent Confidence Intervals for Extra Pavement Width (ft)	
Case No.	Lower	Upper
1	–27.5	23.1
2	–15.5	20.5
3	–19.6	25.4
4	–24.7	17.8
5	–37.4	10.0
6	–17.3	19.9
7	–2.8	29.8
8	–22.3	23.5

pavement width required at the beginning of a simple-curve right turn of urban diamond interchanges is between –27.5 and 23.1 ft.

The negative tail of the interval indicates interchanges with adequate geometry or surplus, and the positive tail describes inadequacy of urban diamonds where the rear wheels of the LCV would encroach up to 30 ft from the pavement edge into neighboring land space. Encroachment of this magnitude, however, occurs only for a large angle and small radius of turn at a highly confined ramp terminal.

Table 4 also presents the difference in the intervals between the eight cases as indicated by the ANOVA procedure. For example, if one looked at only the lower limits, the values are lower for left turns than for right turns at both urban and rural interchanges, indicating the extra pavement width available for left turns. Furthermore, the lower limits for left turns at urban diamonds are higher in magnitude than those of rural diamonds, signifying higher design levels for diamond interchange ramp terminals at urban areas than those located at rural areas. These observations can also be made from the upper limits. The positive or upper limits are higher for right turns than for left turns at both urban and rural diamonds, indicating that inadequate geometry for right turns was more critical than for left turns.

CONCLUSIONS

The main objective of the research presented was to assess the adequacy of the geometry of diamond interchanges located along the Interstate highways in Texas to accommodate the offtracking of LCVs. Because the assessment drew inferences about the entire population of diamonds, the results could only be interpreted as interval estimates for a chosen confidence level, in this case 95 percent. The preliminary analysis using the ANOVA procedure revealed that the location and movement type significantly affected the pavement areas available at the diamond interchange ramp terminals, and thus the following conclusions were based on these two main effects.

At least 92 percent of urban diamond interchanges were estimated to be incapable of accommodating right-turn maneuvers by the LCVs and could require additional pavement widths up to 25.4 ft, depending upon the radii and angles of turns. This estimation was made at a confidence level of 95 percent. The proportion of similar diamonds that had geometry inadequate to accommodate left-turn maneuvers ranged from 84 to 99 percent at 90 percent confidence level, and the extra pavement widths required at their ramp terminals could reach 20.0 ft. The rural diamonds were estimated to have a higher proportion of right turns than the urban diamonds, that is, 94 percent or higher, and up to 30.0 ft of extra pavement width could be required at their ramp terminals; thus the rural diamonds were more critical than the urban diamonds. The proportion of rural diamonds with inadequate geometry for left-turn maneuvers ranged from 83 to 97 percent at a 90 percent confidence level and may require up to 24.0 ft of extra pavement width.

If the LCVs are introduced into the Texas Interstate highway system, the geometry of the existing diamond interchange ramp terminals needs to be improved significantly to prevent damage to pavement edges and other roadside appurtenances by the rear wheels of the LCVs. Furthermore, the rural diamonds were found to be more critical than the urban diamonds due to their lower design level. In both cases, the right turns again needed greater attention than the left turns.

An inexpensive and expedient technique to determine the exact improvement needed for a chosen ramp terminal would be to simulate a chosen LCV on the existing terminal using the TOM as discussed in this study. The offtracking plots from the TOM can then be used as new design templates to redesign or upgrade the geometry of existing diamond interchange ramp terminals.

Although the results of this research were applied to diamond interchanges in Texas, the methodology of using the ANOVA procedure, the determination of the proportion of interchanges with inadequate geometry, and the estimation of extra pavement width required from sampled interchanges can be readily adopted by others. The successful use of the ANOVA procedure on the data collected in this research as a screening process to determine the significance of the factors involved reveals the usefulness of this procedure as a tool for engineers in statistical analysis. Therefore, by varying the inference space of the locations where the data is collected and conducting similar ANOVA analysis, the significant factors involved in expressing the dependent variable of interest can be determined, instead of using other laborious and time-consuming techniques to arrive at conclusions equivalent to those of the ANOVA procedure.

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